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Review

Long-term effects of wastewater reuse on hydro physicals characteristics of grassland grown soil in semi-arid Algeria

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ABSTRACT

The raw and treated wastewaters are often evacuated downstream of settlements and widely reused in pre-urban agricultural irrigation. Our study highlights the impact of wastewaters on the soil hydro-physical properties as well as biological activity.

Our study was conducted in eastern part of Algeria, on long-term (>60 years) wastewater irrigated grassland to determine the biological component and hydrodynamic soil behavior under these practices. Effects of three wastewater types (raw urban, treated and agricultural effluents) on soil were studied and water was characterized both physically and chemically. Assessment of the effects involved soil porosity, soil hydraulic conductivity and earthworms' abundance.

The results revealed that waters contain high concentrations of organics (BOD 5&COD) and suspended solids (SS). Hydro-physical properties and biological activity showed that irrigation with raw urban wastewater enhances soil earthworm density, porosity and higher water transfer via hydraulic conductivity. Biological activity resulted in ideal pore architecture for materials and solutes transfer, induced a variety of micro morphological transformations in relation to the abundance of earthworm communities mostly endogeic and anecic.

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1. Introduction

Humanity faces the challenge of achieving sustainable agricultural production, while increasing crop yields and reducing soil and water losses (Sharma et al., 2017a). The arid and semi arid regions of Algeria are characterized by excessive water evaporation throughout the year. Seeking high yields, farmers often resort to irrigation, but confronted with the major problem of water shortage. For several decades, freshwater resources for irrigation have become scarce (Tamrabet et al., 1999; Mouhouche and Guemraoui, 2004; Hadibi et al., 2008), and thus emphasis was placed on the use of unconventional water resources. Treated wastewater is a reliable source of water and nutrients for crops (Jimenez Cisneros, 1995) to ensure sustainable agriculture.

Wastewaters usually contain high amounts of plant nutrients (Stevens et al., 2004), which reduce the use of costly chemical fertilizers, and enhance soil fertility and crop productivity (Saenz, 1986; Faruqui, 2002; Stevens et al., 2004; Mukherjee and Nelliyat, 2007). Wastewater reuse in agriculture is an old practice around the world (Scott et al., 2004; Buechler and Gayathri Devi, 2006), which has been practiced for centuries in Mexico and China (Shuval et al., 1986). This practice is a way to reduce pressure on freshwater resources which are primarily directed for human and industrial uses, and to dispose waste as well (Shuval et al., 1986; El Hamouri, 1996,1998; Levy et al., 1999; Niang, 1999; Hajjami et al., 2012; Faruqui, 2002; Cheftez et al., 2006). Wastewater is considered by *peri*-urban farmers as an opportune free water resource, rich in fertilizers (Tamrabet, 2011). However, the use of treated wastewater may have impacts, either on crops (Yadav et al., 2002) or on physical and chemical properties of soils (Tarchouna et al., 2010, Levy et al., 1999; Mamedov et al., 2000). Changes in soil physical and chemical properties, due to irrigation with treated wastewater, can affect the hydro-dynamic properties of soils (Tarchitzky et al., 1999).

In Algeria, there is little information on the impact of wastewater irrigation on the physical, chemical and hydraulic properties of soil. Consequently, there is a need to understand potential environmental impacts of this practice. Because Soils are not only important for storing and supplying water; they also filter as bioreactors that contain charged surfaces at which exchange reactions can occur, such as bacteria, fungi and soil animals that process nutrients and contaminants, and act as a medium to support plant growth that cycles nutrients and water through the ecosystem it (Keesstra et al., 2016).

There is no consensus in the scientific literature on the effects of irrigation with wastewater on soil physical properties, particularly on hydraulic conductivity. Many studies agree, on one hand, that soils irrigated with wastewater have a significant reduction of the hydraulic conductivity (Vinters, 1983; Cook et al., 1994; Halliwell et al., 2001; Viviani and Lovino, 2004; Bhardwaj et al., 2007; Gharaibeh et al., 2007; Schacht and Marschner, 2015). Siegrist (1987) states that this clogging of the pores concerns the surface layer of the soil. On the other hand, other authors have mentioned a positive effect of the use of wastewater on the physical properties of soil. Agassi et al. (2003) concluded that domestic effluents do not adversely affect hydraulic parameters and the stability of agricultural land in the absence of drainage problems. Chenini et al. (2002) and Minhas and Samra (2004) demonstrated an improvement in total porosity and hydraulic conductivity.

Soil fauna and flora are important to soil quality and reduce risks of degradation and desertification. Indeed, soil biota comprise a major component of global terrestrial biodiversity and perform critical roles in key ecosystem functions (Lal, 2015) and is involved directly and indirectly in many soil functions (Cluzeau et al., 2009). Although the soil fauna has been shown to have profound impacts on soil ecosystems and to regulate many important soil processes (Bender et al., 2016).

Earthworms are an essential component in sustainable agricultural systems because they alter physico-chemical and biological regimes of the soil through their activities, such as burrowing, casting, feeding and propagating. Through their activities, they provide a number of ecosystem services (Sharma et al., 2017a). They help maintain and enhance the physical conditions and functions of soils. Their contribution, such as the water flow, nutrients and gases, is influenced by their abundance and diversity (Schon et al., 2017).

The earthworm burrows contribute to macroporosity and so influence water infiltration and aeration. (Lee and Foster, 1991).

The anecic species represent 40–60% of the biomass of earthworms in the soil (Ménard, 2005). Anecic and endogeic species are responsible for a majority of physical improvements in soil structure through cast production in vertical and horizontal burrows (Sharma et al., 2017b). *Anecic* earthworms dig vertical burrows and feed in the litter. Non-pigmented *endogeic* earthworms, which feed and live in the soil, contribute most to soil aggregation (Marichal et al., 2017).

Because the soils are a key body in the earth system. The main objective of this study was to evaluate the impact of irrigation with different types of wastewater on the hydro-physical properties and on the earthworms' activity during 60 years under permanent grasslands of the *peri*-urban areas of the High Plains of Eastern Algeria. To our knowledge, no study to date has detected the impact of wastewater irrigation on both physical and biological soil compartments. In addition the objective was to determine and know which is the best type of water among the three types used which has positive effects on the soil by increasing the porosity, the hydraulic conductivity as well as the abundance earthworm.

2. Material and methods

2.1. Presentation of the study area

The study was conducted in the *peri*-urban area of Setif (36° 11′29 N, 5° 24′ 34 E) which is located in the high plains of eastern Algeria, at 900 m above sea level. Climate is continental semi-arid, with hot and dry summer and, cold and wet winter. Rainfall is low and irregular, ranging from 228.1 to 503.8 mm/year. The study was conducted in Bousselam valley which lies west of Setif city, with decreasing altitude from 1100 m to 970 m, in the north to south direction. Bousselam River is a permanent stream surrounded by a late quaternary plain covered by calcisols (WRB, 2006) while silty clay loam calcareous Fluvisols developped on alluvial deposits occurring on both river sides.

To carry out this work, three sampling sites were selected from upstream to downstream along the valley at different feeding sources: the discharge site of raw urban wastewater (S1), the discharge site of treated wastewater with activated sludge (S2) and the discharge site of agricultural effluents (S3).

The physicochemical characterization of the soils irrigated by submersion method with the three types of effluents is carried out on a surface layer of 0–10 cm by the measurement of pH, organic matter, $CaCO_3$ content, soil texture was measured by pipette method according to Day (1965), organic matter in the soil was determined by wet combustion method as described in Nelson and Sommers (1982), pH was measured directly by pH/mV meter (UB- 10. Denver instrument. Ultra Basic).

Bousselam River is the main water source for Ain Zada dam, it carries wastewater of Setif city as well as agricultural effluents (Limani, 2008; Bentouati and Bouzidi, 2012).

2.2. Wastewater sampling

Water chemical characterization was performed on samples, taken in autumn 2012, in polyethylene bottles of 1.5 L, at the three sites (S1, S2, S3). All water samplings were done in four replicates at each site in the same date. Temperature, pH, electrical conductivity (EC), dissolved salts (DS), turbidity and dissolved oxygen (DO 2) measurements were carried out in-situ. Chlorides (Mohr method), nitrates (in the presence of sodium salicylate at 415 nm), phosphates (by 700 nm molecular absorption spectrometry), sulphates (by the nephelometric method at 650 nm) and ammonium (Spectrometric measurement at 655 nm), calcium and magnesium (by complexometry with a solution of EDTA and as a colored indicator: murixide) were analyzed according to Rodier et al. (2009).

The amount of suspended solids (SS) was obtained by centrifugation according to Rejsek (2002), biological oxygen demand (BOD 5) measurements were made using a BOD-meter and the chemical oxygen demand (COD) with a COD-meter. Na, K, Fe, Cu, Mn and Zn were analyzed by atomic absorption spectrophotometry.

2.3. Earthworms sampling

Earthworms were sampled according to the method of Raw (1959), using formalin: 25 ml of formaldehyde (40%) diluted in 4.56 L of water and spread over $0.6\ \text{m} \times 0.6\ \text{m}$ ($0.36\ \text{m}^2$) for

15 min. Then, manual sorting is applied to the volume of sampled soil at a depth of 0.2 m.

The number, age and species of earthworms were determined on 5 replicates per site.

2.4. Soil bulk density and porosity

The soil bulk density was measured, at 5 cm depth, on four replicates with metallic cylinders of $250\ \text{cm}^3$. The porosity was derived from the soil solid density ($2.65\ \text{g/cm}^3$).

2.5. Soil hydraulic conductivity near saturation

Hydraulic conductivity near saturation K(h) was measured in-situ at four different pressure potentials (−1.5, −0.6, −0.3 and −0.06 kPa). Measurements were started from the lowest pressure (−0.06 kPa) to the highest pressure (−1.5 kPa), four replicates in each site were carried out, using a multi-drive blower suction controlled TRIMS (triple-ring infiltrometer with multiple suctions) with 80 mm mean diameter at 5 cm depth. Due to the similarity between the experimental methods of soil hydraulic characterization, Di Prima et al. (2017a) indicate that the use of an infiltrometer seems logical in the study of water infiltration processes.

2.6. Soil surface porosity by image analysis

Description of pores morphology has been carried out on undisturbed structure of soil blocks of 12 cm × 6 cm × 6 cm in dimensions, taken at the infiltration sampling tests (Kribaa, 2003; Hallaire et al., 2004). The samples were dehydrated by acetone water exchange (Murphy, 1986), to prevent the formation of cracks during drying, before being impregnated with a resin containing inclusion of a fluorescent dye (Murphy et al., 1977; Ringrose-Voase, 1996). After hardening, the blocks were cut horizontally with a wet saw, into three slices and gave five smooth sections. Images were captured on five sections of each block, under UV light which excites the fluorescent pigment wherein the solid phase is dark and the pores are bright because of the filling resin (Ringrose-Voase, 1996). This work is carried out using an optical microscope (Leica DM LP) under reflected ultraviolet light. Images were taken using a camera DC200 in two spatial resolutions of 5.88 μm/pixel and 2.63 μm/pixel and a spectral resolution of 256 grey levels.

Image analysis was performed using the Visilog software. In each block several images were seized. Typological classes of pores were obtained by the index of elongation [$e = (\text{perimeter})^2/4\ \pi\ \text{area}$] (Coster and Chermant, 1985; Lamandé et al., 2003). Three classes of shapes: rounded pores ($e < 5$), Cracks ($5 < e < 10$) and packing voids ($e > 10$) and four size classes were defined (Table 1).

2.7. Data analysis

Collected data were subjected to descriptive statistics analyses, analysis of variance, and principal component analysis using, Cropstat 7.2.3 (2007) and Past (Hammer et al., 2001) softwares. ANOVA was also performed to assess differences in soil hydro physical and biological properties between the three irrigation practices.

Table 1
Typology of porosity by size and shape for the two spatial resolutions.

Total number of images	Spatial resolutions and image area	Typological Classes in μm2	Class of shape		
			e < 5	5 < e < 10	e > 10
8 images by smooth section = 40 image/ block	5.88 μm/pixel image resolution 1798x1438 pixels => 89.42 mm^2	a < 7000 7 × 103 < a < 7 × 104 7 × 104 < a < 7 × 105 a > 7x105	A1	B1	C1
			A2	B2	C2
			A3	B3	C3
			A4	B4	C4
8 images by smooth section = images by = 40 image/block	2.63 μm/pixel image resolution 1272x1017pixels =>8.95 mm^2	a < 800 8 × 102 < a < 8 × 13 8 × 103 < a < 8 × 14 a > 8 × 104	A1	B1	C1
			A2	B2	C2
			A3	B3	C3
			A4	B4	C4

Table 2
The physical and chemical properties of silty clay loam calcareous Fluvisols (grassland grown soil).

Soil/site	Clay %	Silt %	Sand %	OM %	pH	CaCO3 %
S1. soil irrigated with raw urban wastewater	39	48	13	2.8	7.7	15.5
S2. soil irrigated with treated wastewater	37	49.5	13.5	2.4	8.0	15
S3. soil irrigated with agricultural effluents	36	45	19	1.8	8.1	18.5

Table 3
Average values with standard deviations of the physicochemical characteristics of the water quality.

	T *25 °C	pH *6,5–9 **6,5–8,5	EC (μS/cm) *2800μS/cm **3dS/m	Turb (NTU)	SS *25 mg/L **30 mg/L	DS (mg/L)	Cl (mg/L) *600 mg/L **10 meq/L	Ca (mg/L)
S1	21.38 ± 0.04	8.4 ± 0.025	1710 ± 45.5	486 ± 78.75	587 ± 45.98	1133 ± 46.42	669.8 ± 51.95	57.45 ± 8.415
S2	23.44 ± 0.48	8.28 ± 0.04	1950 ± 4.71	312 ± 136.8	486 ± 74.58	1283 ± 20.54	1110 ± 148.06	35.55 ± 4.73
S3	19.06 ± 1.57	8.06 ± 0.15	1520 ± 295.9	60 ± 61.91	273 ± 72.06	1060 ± 209.60	621 ± 164.63	32.06 ± 11.50
	Mg (mg/L)	Na (mg/L)	K (mg/L)	NO3 *50 mg/L **30 mg/L	NH4 *4 mg/L	SO4 *400 mg/L	PO4 (mg/L)	Dis O2 *30 mg/L
S1	45.2 ± 2.47	97 ± 35.10	38.7 ± 4.21	1.41 ± 0.62	0.088 ± 0.001	0.04 ± 0.00	0.45 ± 0.04	1.55 ± 0.51
S2	39.86 ± 3.57	88 ± 7.69	25.56 ± 1.07	0.54 ± 0.01	0.062 ± 0.002	0.04 ± 0.00	0.085 ± 0.02	3.88 ± 1.04
S3	65.61 ± 17.7	41.6 ± 28.71	23.1 ± 1.72	0.53 ± 0.01	0.048 ± 0.004	0.04 ± 0.00	0.12 ± 0.08	2.41 ± 0.85
	BOD 5 *7 mg/L **30 mg/L	COD *30 mg/L **90 mg/L	Cu *2 mg/L **5 mg/L	Fe (mg/L)	Mn *1 mg/L **10 mg/L	Zn *5 mg/L **10 mg/L		
S1	235 ± 2.87	294 ± 3.68	0	0	0	0.021 ± 0.008		
S2	226 ± 10.21	283 ± 12.65	0	0	0	0.122 ± 0.11		
S3	31 ± 8.28	39 ± 10.09	0	0	0	0.028 ± 0.01		

[*] Algerian Standards for surface waters (JO. No 34, 2011).
[**] Algerian Standards for treated wastewater used for irrigation purposes (MRE, 2012).

3. Results and discussion

Soil chemical and physical properties (0–10 cm depth), determined in three locations are presented in Table 2. No big differences between the three sites. The pH is alkaline. The texture is clay-silty. The only parameter that shows some differences between the three sites is the organic matter where the lowest value is recorded for the irrigated site with the agricultural effluents, while the highest is found in the irrigated site with the waters raw urban waste.

3.1. Wastewaters physico-chemical characteristics

Wastewaters physico-chemical characteristics were sumarised in Table 3. Water temperature is an important factor in the aquatic environment because it influences the physicochemical and biological reactions (Chapman and Kimstach, 1996). Average temperatures measured *in situ* for the three effluent types were below 25 °C, which is considered as an upper temperature limit of Algerian surface water. Average temperatures recorded were 21.38, 23.44 °C and 19.06 °C for S1, S2 and S3 sites, respectively. The pH has an alkaline character with the lowest values recorded on agricultural effluents with an average of 8.06. The recorded values remain within the Algerian standards of surface waters pH from 6.5 to 9. The values obtained are slightly higher than those found by Bentouati and Bouzidi (2012) and Kebich et al. (1999) who reported a pH ranging from 7 to 7.69.

Electrical conductivity (EC) obtained exceeded 1000 μS/cm at the three sites, revealing significant water mineralization. A high value of 1950 μS/cm was measured at the treated wastewater discharge site, and this is due to the nature of discarding, which is very high in mineral salts and agricultural water leaching. Compared to surface water Algerian standard, EC values recorded in the present study were slightly lower. Nisbet (1970) in Belghyti et al. (2009) reports that values between 449.7 μS/cm and 1037 μS/cm show strong mineralization. The obtained values reveal significant mineralization of the waters where the EC exceeds 1000 μS/cm.

Leached soils accumulate more soluble salts in the depth (Abu-Awwad, 1996). Mohammad and Mazahreh (2003) mentioned that increased conductivity of soils irrigated with wastewater compared to soils irrigated with fresh water is attributable to the high level of dissolved solids in wastewater.

The turbidity of the water originates from the presence of suspended matter. The highest average values are recorded at the raw urban wastewater discharge site (486 NTU), and the lowest are measured at the agricultural effluents discharge site. These moderately high values indicated that water is trouble, charged with colloids and suspended organic matter. High value of suspended solids was recorded at the raw urban wastewater discharge site with an average of 587 mg/L. This value is 23 times higher than average of surface waters Algerian standard. This is likely due to the quality of wastewaters generated by urban centers, agricultural effluents, solid wastes dumped on the banks of the river, and leaching of the neighboring farmlands. Kebich et al. (1999) reported lower values especially for the urban site. This stresses the temporal variability in the quality of the discharge. Suspend solid (SS) comes out either from the effects of natural erosion of the watershed due to heavy rainfall or from discharges of urban wastewaters. They affect significantly the physicochemical characteristics of water, bringing changes in its turbidity, transparency and light penetration. Chloride (Cl) concentrations in water are extremely variable and mainly related to the nature of the formations crossed (Rodier, 1996). Value of 1.11 g/L exceeding Algerian standard was recorded at the treated wastewater discharge site. This high figure may be due to the nature of the treatments followed at the wastewater treatment plant. Low values were recorded for hardness parameters: Ca and Mg. Maximum value of Ca was recorded at raw urban wastewater discharge site, while agricultural effluents discharge site had maximum value of Mg (Table 3). For Na and K, generally high average values are recorded in both raw urban and treated wastewater sites, while the lowest values are recorded for agricultural effluents sites (Table 3).

Table 4
Mean square analysis of variance on the measured parameters.

A/Waters characteristics

TC°	**pH**	**EC**	**Turb.**	**DS**	**Cl**	**Ca**	**Mg**	**Na**	**K**
19.2***	0.11**	0.001 **ns**	183906.5**	51837.08 **ns**	289982.6**	757.65**	739.13*	3525.2*	281.28***
NO3	**NH4**	**SO4**	**PO4**	**SS**	**DO 2**	**BOD5**	**COD**	**Zn**	**/**
1.01*	0.001***	0.00**	0.16***	102877.5***	5.54*	53325.5***	83343.3***	0.01 **ns**	/

B/Physico-hydric parameters and earthworms

Parameters	K(0.06)	K(0.3)	K(0.6)	K(1.5)	Porosity	Total earthworm	Juvenile	Mature
MS	23.6275**	155.882**	816333**	1.16218**	263.175**	603*	525**	3**ns**

C/Size and shape parameters of the surfacic porosity

Parameters	PS (5.88)	A(5.88)	B(5.88)	C(5.88)	CT1(5.88)	CT2(5.88)	CT3(5.88)	CT4(5.88)
MS	58.20 ns	14.20 ns	3.48 ns	4.04 ns	156434 ns	3.00 ns	8.19 ns	17.54 ns
Parameters	PS(2.63)	A(2.63)	B(2.63)	C(2.63)	CT1(2.63)	CT2(2.63)	CT3(2.63)	CT4(2.63)
MS	18.39**	9.59**	654262*	3.51**	280022ns	1.06ns	2.50*	8.11*

K(0.06), K(0.3), K(0.6), K(1.5) Hydraulic conductivity at pressure potentials of 0.06 – 0.3 – 0.6 and 1.5 kPa. PS: Surfacic porosity, A: tubular voids, B: cracks, C: Packing voids, CT: (1,2,3,4) class size.
ns non significatif **$P > 0.05$**; * significatif **$P < 0.05$**; ** highly significatif **$P < 0.01$**; *** very highly significatif **$P < 0.001$**.

Results of nitrogen compounds showed that Bousselam River waters were not N-polluted, since low values, below standards, were recorded, with maximum values of 1.41 mg/L, NO3 and 0.088 mg/L, NH4, measured at the urban discharge site. These results didn't corroborate those of Kebich et al. (1999) who reported high nitrate and ammonium concentrations. Derwich et al. (2010) mentioned that sulfates content of surface waters varied widely, Sulfates content, at the three discharge sites, was low with an average of 0.04 mg/L, which is 10,000 times lower than the standard. Orthophosphate content was very low, too, hardly exceed 0.5 mg/L, suggesting no risk of eutrophization. Dissolved oxygen conditions the aerobic degradation reactions of organic matter and more generally the biological balance of aquatic environments (Belghyti et al., 2009). The dissolved oxygen concentrations vary depending on the type of wastewater. In the present study, highest average values are recorded at treated wastewater discharge site with 3.88 mg/L and the lowest values at raw urban wastewater discharge site (1.55 mg/L). These values are significantly low compared to standard of surface water quality (30 mg/L). Results of samples analysis showed high values of BOD 5standard (7 mg/L), being 4–34 times above. It is worthy to note that agricultural wastewater site, had a low BOD 5 value of 31 mg/L, compared to the other sites. Value of chemical oxygen demand (COD) of the agricultural discharge site, slightly exceed allowable standards of 30 mg/L for surface water and 90 mg/L for wastewater reused for irrigation. Urban and agricultural effluents exhibited higher values up to nine times the standards average.

Heavy metals present in wastewater are fixed in the soil. Nonetheless they are a small part in irrigation water (Landreau, 1987; Cadillon, 1989).

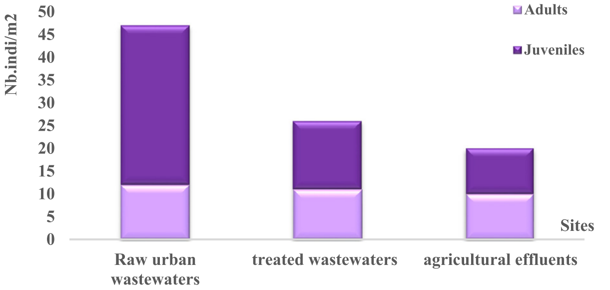

Fig. 1. Abundance of adult and juvenile earthworms in irrigated soil according to wastewater type.

Analyses made for Fe, Cu, Mn and Zn, showed the absence of Fe, Cu, Mn with the presence of low concentrations of Zn compared to surface water quality standard of 5 mg/L, and to treated wastewater standard used for irrigation purposes of 10 mg/L.

A statistical analysis was conducted for all measured parameters to test the interactions. Analysis of variance results (Table 4/A) of wastewater characteristics showed highly significant effect for potassium, ammonium, phosphate, DS, BOD5 and COD, type of irrigation water. Thus highly significant correlations for pH, turbidity, Cl, Ca, SO4, K (0.06), with the types of water used in irrigation. While the EC, DS and Zn showed no significant difference.

3.2. Impact of wastewaters on soil

3.2.1. Impact on soil macro biology

The results of this study show the dominance of three earthworm species belonging to two families Acanthodrilidae (*Microscolex phosphoreus* endogeic species) and Lumbrucidae (*Allolobophora caliginosa* endogeic species and *Octodrilus lissaensis* anecic species). The practice of irrigation with different types of water influences the total abundance of earthworms. Irrigation with raw urban wastewater promotes the abundance of worms with a mean value of 47 ind./m^2. This value is twice the total number of earthworms obtained in irrigated sites with agricultural effluents and treated wastewaters (Fig. 1). Bottinelli (2010) reported a higher number of earthworms in poultry manure intake compared to mineral fertilization. Anderson et al. (1983) indicated that an intake of slurry or manure positively influences the populations of earthworms. Pelosi (2008) reported that the abundance of earthworms depends on culture systems and on the exerted human pressure. These results suggest that the quality of irrigation water influences the abundance of earthworms and mainly the high concentration of particulate and organic matter.

Fig. 1 shows that the worms harvested at the irrigated site with raw urban wastewaters were 78% juveniles and 22% mature. Treated wastewater discharge site had a higher percentage of mature worms (42%), while at the irrigated site with agricultural effluents; the relative abundance of juvenile and adult worms is similar.

A variance analysis was carried out (Table 4/B) on all charged to earthworms. It appears that the adult worms have an insignificant effect upon the studied treatments, while the total abundance of earthworms has marked a significant effect between types of irrigation water. The juveniles reveal highly significant differences on irrigation water quality. These results suggested that irrigation water quality affected the abundance of juvenile worms, which is

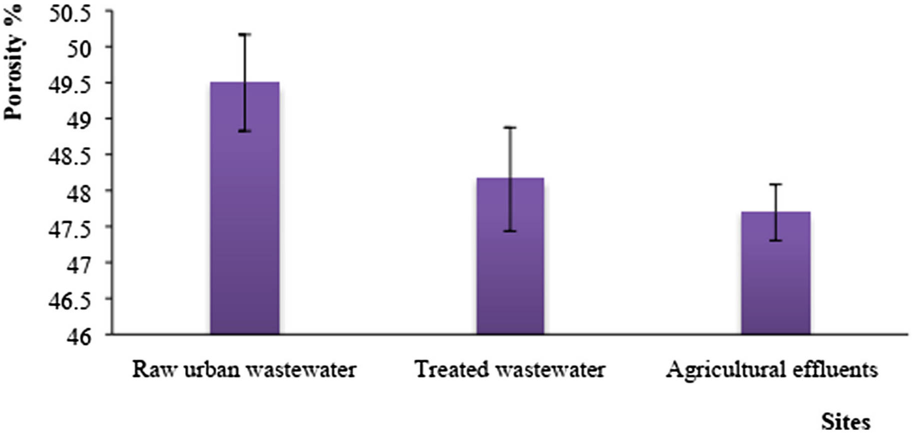

Fig. 2. Total porosity of grassland soils irrigated with the three types of waters.

reflecting on changes in effluent types. Walmsley and Cerdà (2017), conclude that traditional flood irrigation promoted a more abundant and diverse earthworm population, which has the potential to improve the water regime of the soil by creating macropores.

3.2.2. Impact on soil porosity change

The total porosity is a very sensitive parameter to irrigation, biological activity, and water transfer. The values of porosity calculated from the bulk density show a variation of the same order as the abundance of earthworms where soils irrigated with raw urban wastewater are more porous (P = 49.49%), followed by soil irrigated with treated wastewater (Fig. 2). While the soil irrigated with agricultural effluents revealed the lowest porosity values. This indicates that the quality of irrigation water influences the porosity with the same order of its effect on the abundance of earthworms. The richness of raw urban wastewater in organic and particulate matter has favored the abundance of earthworms, which in turn has positively influenced the total porosity of the soil.

Under experimental conditions in microcosms, the results of the study by Schon et al. (2017) indicate that the influence of abundance and high diversity of earthworms resulted in a 70% increase in the number of macropores and a decrease in soil moisture and the high earthworm treatment had 5% more micropores, improving the water holding capacity and plant available water.

3.2.3. Soil pore morphology

Fig. 3, illustrates the surface porosity distribution in soils irrigated by different types of wastewater (raw urban, treated and agricultural effluents). Image analysis is performed according to two (2) spatial resolutions: 5.88 and 2.63 μm/pixel. For these magnifications, the results are consistent with the porosity data as measured based on bulk density. The pores are divided into 12 classes in shape and size.

- Spatial resolution: 5.88 μm/pixel

For this spatial resolution, the majority of the porosity is due to pores having tubular voids (A) for the three types of irrigation water: raw urban, treated and agricultural effluents, with respective percentages of 50%, 60.38% and 57.63%, followed by the packing voids (C). The soils irrigated with raw urban wastewaters have the highest surfacic porosity (8.54%) followed by those irrigated by treated wastewater (7.77%), while the lower surfacic porosity is registered for irrigated soils with agricultural effluents (03.61%). Looking at Fig. 3, the variability of the porosities distributed in classes of size is increasingly high toward the classes of large pores. The results show that the typological class 3 (that is to say pores which have a size comprised between 7×10^4 and 7×10^5 μm^2) is the most dominant size for irrigated soils with different types of water with percentages of 40%, 42.38% and 44.40% respectively for raw urban wastewaters, treated wastewaters and agricultural effluents. As for the soil irrigated with treated wastewater, it is the size of class 2 which dominates (pore size between 7×10^3 and 7×10^4 μm^2) with 33.70%. The rank order of the surfacic porosity is consistent with the results of the macro-morphological porosity as already mentioned. This is due to the effect of the biological activity which follows the same ranking from the abundance point of view.

- Spatial resolution: 2.63 μm/pixel

For this second spatial resolution, the results of the image analysis revealed no differences in the surfacic porosity compared to the first spatial resolutions, where we noticed that the largest surfacic porosity is recorded for irrigated soils with raw urban wastewater followed by soils irrigated with treated wastewater, with a slight difference (7.79% and 7.54%) and the lowest surfacic porosity is recorded for irrigated soil with agricultural effluents (3.96%). Dealing with pore shape, the results always show the dominance of tubular voids (A), with the highest contribution of 47%, 69% and 59% respectively for soils irrigated with raw urban wastewaters, treated wastewaters and agricultural effluents. Regarding the pore size, the results show that the typological class 3 (that is to say pores which have a size of between 8×10^3 and 8×10^4 μm^2) is the size that dominates with contribution rates, in the surfacic porosity, of 37.5%, 43.93% and 43.37% respectively for the three waters of irrigation. It is obvious to note that for irrigated soil with raw urban wastewaters, both typological classes 3 and 4 (that is to say pores which have a size ranging from 8×10^3 to 8×10^4 μm^2 and >8×10^4 μm^2), contribute with a similar percentage in the surfacic porosity which represents about two thirds of the surfacic porosity. An analysis of variance was performed on all size and shape parameters of the pores (Table 4/C). It appears that the majority of these types of pores present for this spatial resolution presents significant differences ($P < 0.05$ and 0.01) between the studied treatments. This same ANOVA shows no significant differences ($P > 0.05$) for typological class 1 and 2.

3.2.4. Change in hydraulic conductivity near saturation

The hydraulic conductivity is used to determine the hydrodynamic characteristics of the soil. It explains the transfer of water in the soil (Kribaa, 2003). The increase in suction potential gener-

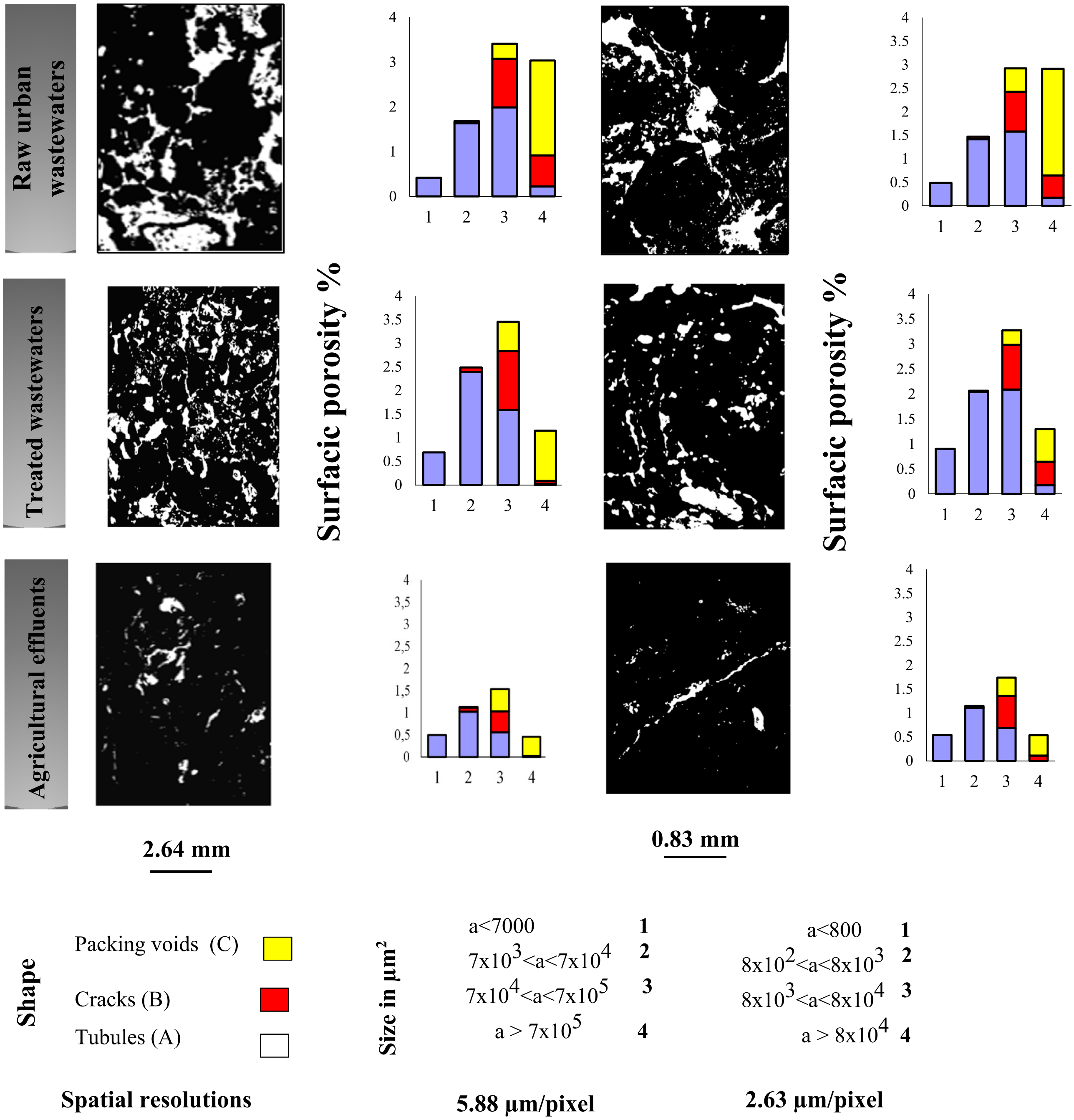

Fig. 3. Pore classification according to size and shape for the three irrigated soils with two spatial resolutions.

ates a strong decrease of hydraulic conductivity in the vicinity of the saturation, the higher the slope is between two potentials, the more increase is in the functional porosity, with a remarkable variation in the first two pressure potentials (0.06 kPa and 0.3 kPa) (Fig. 3) where in soils irrigated with raw urban wastewater have recorded the highest values (2.04E−05 and 9.16E−06 m/s successively for the two pressure potentials) followed by soil sites irrigated by treated wastewater (1.94E−05 and 6.57E−06 m/s).

Soils irrigated with agricultural effluents have the lowest values of hydraulic conductivity (1.88E−05 and 5.22E−06 m/s) which can be attributed to the decrease in the functional macro bio porosity. Moreover, for the potentials (0.6–1.5 kPa), the hydraulic conductivity is almost identical for the three sites with hydraulic conductivities <3E−06 m/s for the pressure potential (0.6 kPa) and lower than 1.5E−06 m/s for the pressure potential (1.5 kPa). This suggests that low suctions (0.06 kPa and 0.3 kPa) reflect the effect of the type of irrigation water. Chalhoub et al. (2009) indicate that the increase in hydraulic conductivity is usually due to the presence of pore radius strictly >0.25 mm. All variables of the hydraulic conductivity exhibit highly significant differences between the studied treatments (Table 4/B). Following this statistical summary, we show that the types of water greatly influence the water transfer of the soil. Lado and Ben Hur (2010), indicate that the hydraulic conductivity is among the parameters that may be affected by irrigation with effluents. In our case, the type of effluent influenced the hydrodynamic parameters of the soil, by increasing the hydraulic conductivity (See Fig. 4).

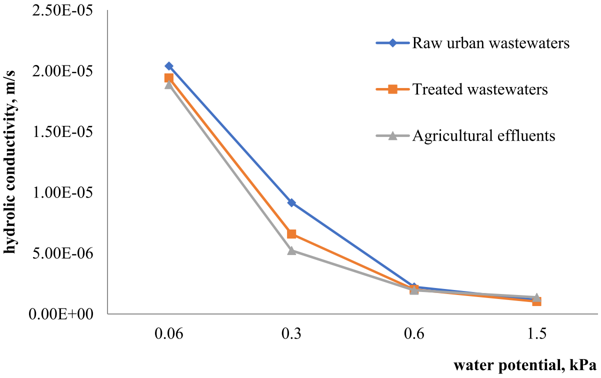

Fig. 4. Average values of hydraulic conductivity near saturation versus suctions (kPa) at the three sites.

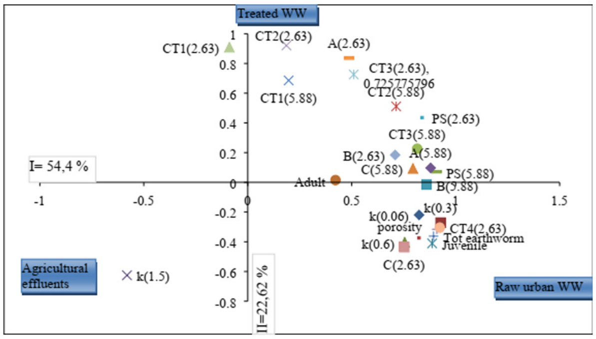

Fig. 5. Representation of the dispersion of individuals in the F1 × F2 plane of the PCA.

Soils irrigated with raw urban wastewaters recorded the highest values of hydraulic conductivity for the first two low pressures, despite of the fact that the raw urban wastewaters are loaded with SS and organic matter. This high organic and particulate load favors the abundance of worms, which promotes hydraulic conductivity near saturation, where the involvement of earthworms favored the increase of hydraulic conductivity and limited clogging of the pores, by the bioturbation activity which ensures the creation of porosity and the transfer of matter.

Di Prima et al. (2017b) concluded that, the presence of a significant macropore network, high root and soil fauna density and activity and water repellent behavior of the soil resulted in a sharp increase of the hydraulic conductivity when moving from near-saturated to saturated conditions.

As already mentioned, the order of ranking of the surface porosity is consistent with the results of macromorphologic porosity for the two spatial resolutions, this is due to the effect of the biological activity which follows the same ranking from the earthworm abundance point of view. We conducted a Principal Component Analysis (PCA) to graph the correlation between the parameters of the macro and micromorphology and earthworms (adult, juvenile and total earthworm) in the three sites (Fig. 5). The correlation matrix indicates a positive significant correlation between the porosity and juvenile (r = 0.95).

This obtained correlation follows that of Allison (1973), where they indicate that the tunnels dug by earthworms tend to decrease the soil bulk density and increase the aeration and drainage. Lamandé et al. (2003) noted that complex pores are a good indicator of soil permeability. Our results revealed positive and significant correlations between packing voids and juvenile (r = 0.84) and hydraulic conductivity at two potentials k (0.3) and k (0.6) (r = 0.83, r = 0.78) with the second magnification (2.63 μm/pixel) only.

Overall, the magnification 5.88 μm/pixel shows clearly the contribution of the biological activity of juveniles in improving the surface porosity where we recorded a positively significant correlation between tubular voids (A) (r = 0.99) and surface porosity. Fig. 5 illustrates the largest information given by the axis I (51.35%) with a combination of the two axes of 74.43%. The porosity, total earthworms, juvenile, k (0.3) and k (0.6) are negatively correlated to the axis II and oppose bio pores throughout this axis which are positively correlated to it.

The same graph clearly shows that tubular voids (A) having the largest size for the two magnifications (5.88 μm/pixel and 2.63 μm/pixel). The distribution of variables in the ½ plane allowed to develop a grouping. It is important to note that Group I is related to the site of urban wastewater, while Group II is related to the site of treated wastewater. It is important to point out that the axis I is related to the site irrigated with raw urban wastewater, while the axis II is linked to the site irrigated with treated water. Several authors reported that the activities of earthworms improve soil structure and increase infiltration (Syers and Springett, 1983; Edwards and Shipitalo, 1998). This is consistent with results of the present study which showed significant correlations between the total number of earthworms and hydraulic conductivity near saturation and exactly juveniles which act much where we recorded very significant correlations between juvenile and potential K (h) 0.06 kPa, 0.6 kPa and 0.3 kPa (r = 0.85, r = 0.98 and r = 0.92 respectively). Pores classification, based on morphological criteria, revealed that rounded pores of medium to large size acted on the structural processes followed by the packing voids.

The results clearly showed that raw urban wastewater irrigation improved the porosity of soil. This is consistent with Minhas and Samra (2004) results, who reported an increase in hydraulic conductivity and total porosity in Indian soils irrigated for long times with wastewater. Agassi et al. (2003) mentioned that long term irrigation with domestic effluent showed not negative effects on soil hydraulic parameters. Molahoseini (2014) indicate a reduction of 45% in hydraulic conductivity over 29 years of irrigation practice with wastewater. Significant reduction in hydraulic conductivity was noticed by Viviani and Lovino (2004), on clay soils. Sou (2009) indicated that the decrease in hydraulic conductivity may be due to the clogging of pores which reduced the saturated hydraulic conductivity up to 80% of its initial value. Wang et al. (2003) found that irrigation with treated wastewater reduces soil porosity. It is worth to notice that the results of the present study indicated that it is the type of raw urban wastewater that makes augment the porosity hydraulic conductivity as well as earthworms' abundance.

4. Conclusion

Results showed that irrigation with urban wastewater leads to increased soil earthworm density, porosity and higher water transfer via hydraulic conductivity, although the three types of waters are loaded with organic and particulate matters.

The study of the soil micromorphology showed clear differences in the characteristics of the structure of the pore space for the three irrigation waters. Raw urban wastewater used without treatment led to a large surfacic porosity.

Overall, the results of the porosity with two spatial resolutions (5.88 and 2.63 μm/pixel) are consistent with the porosity measured based on bulk density.

Qualitative analysis of porosity showed that all analyzed images show a biological porosity and medium to large size. This is related to the diameter of earthworm bioturbators. The contribution of biological activity in the soil structure has ideal pore architecture for transporting materials and the transfer of solutes. This biological work, especially in the area of intense activity which is close to the soil surface, showed a variety of micro-morphological changes in relation to the abundance of earthworm communities' mostly endogeic and anecic.

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